Small m_H^2 from Metastability

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Work in collaboration with Thomas Steingasser and Sokratis Trifinopoulos

This talk in a slide

Mystery: SM is not complete, expect additional UV scales Λ, why not $|m_H^2| \sim \Lambda^2$ as expected from QFT?

a) Requiring vacuum metastability

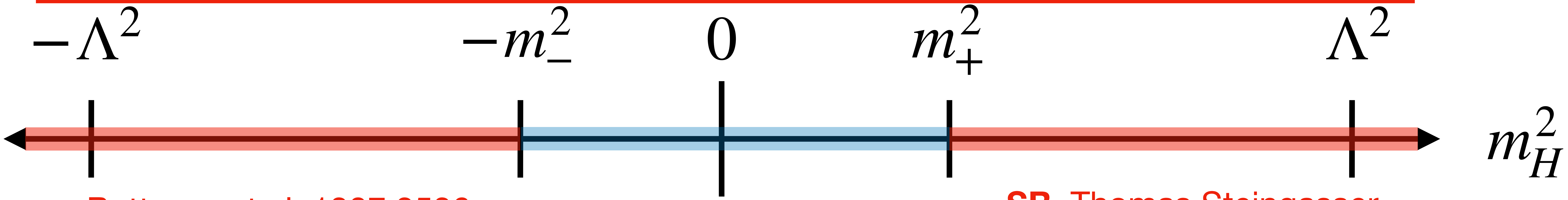
+

b) EFT assumptions

+

Fixed values of SM couplings

$$\Longrightarrow \frac{|m_H^2|}{\Lambda^2} \ll 1$$



Buttazzo et al. 1307.3536
Khoury, Steingasser 2108.09315

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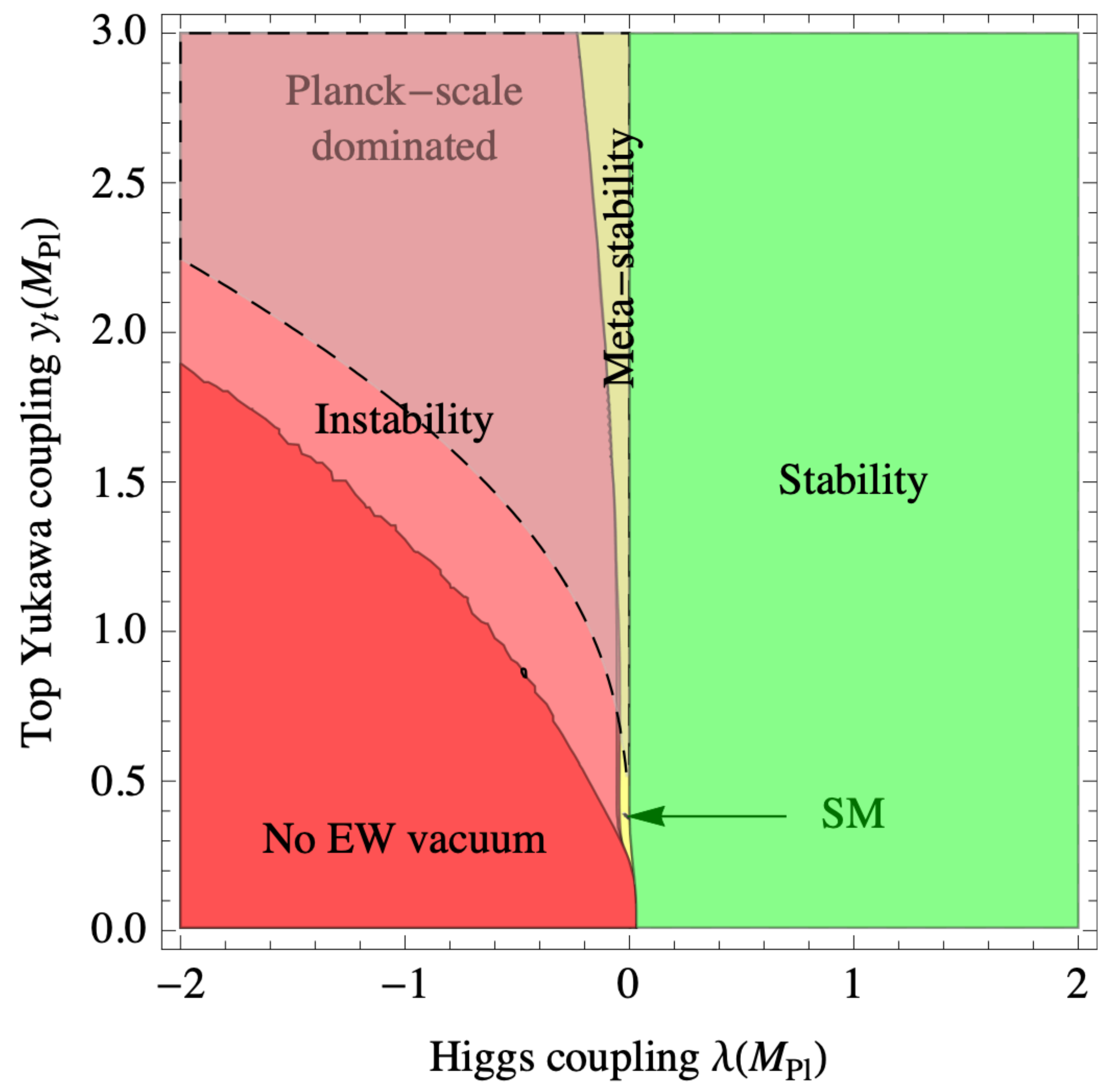
a) Why require vacuum metastability?

Buttazzo et al. 1307.3536



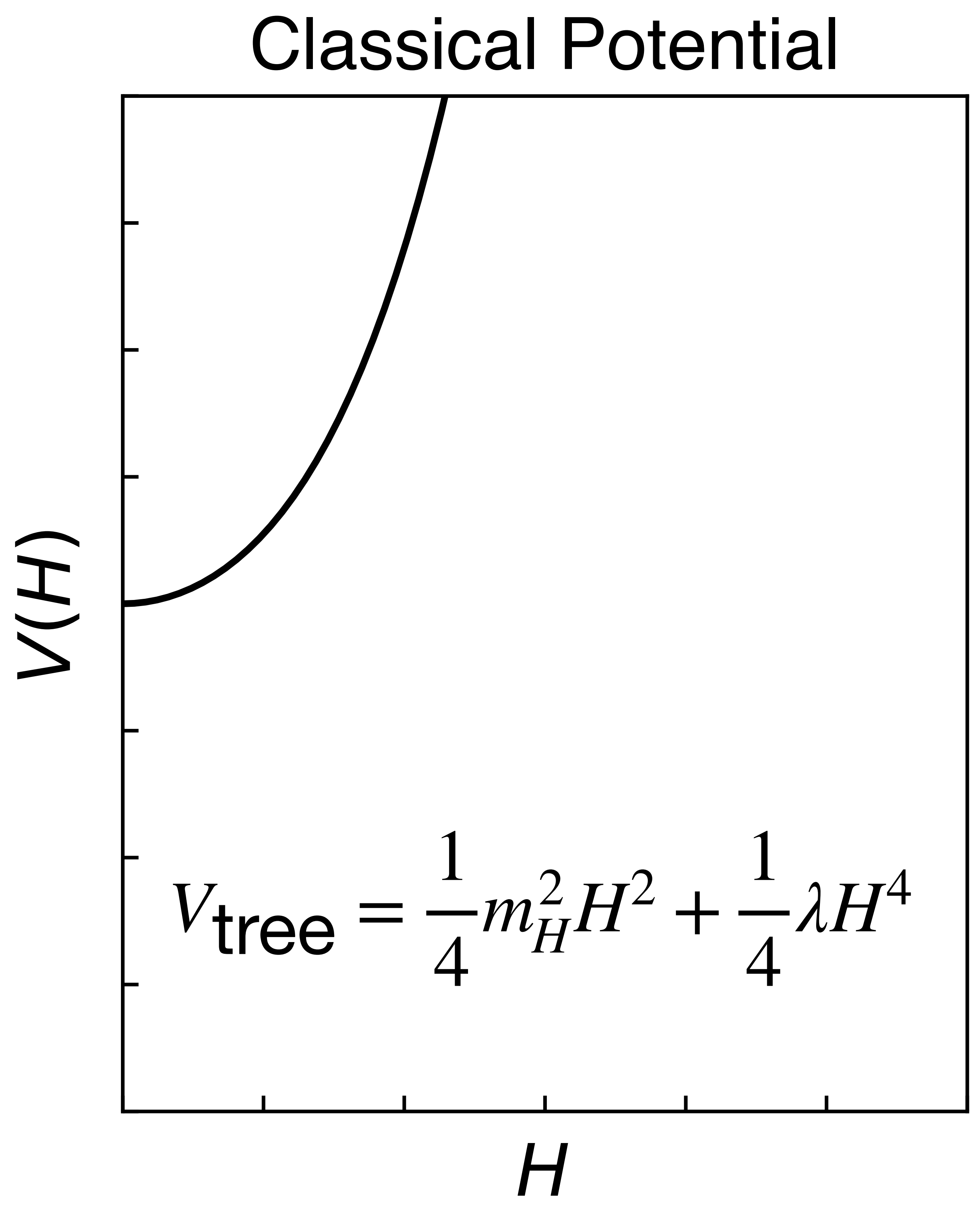
- Current measurements indicate that the SM is already metastable (Degrassi et al. 1205.6497), so in some sense this is the null hypothesis
- Some cosmological scenarios predict a metastable electroweak vacuum
  - Accessibility criterion (Khoury 1912.06706)
  - Self-organized localization (Giudice, McCullough, You 2105.08617)

Our philosophy: Assume metastability and see if it leads somewhere interesting

Anthropic argument: If it didn't lead somewhere interesting, I wouldn't be giving a talk about it

Electroweak vacuum metastability

- Classically: with $m_H^2 > 0$, the Higgs potential attains a minimum at $H = 0$



Electroweak vacuum metastability

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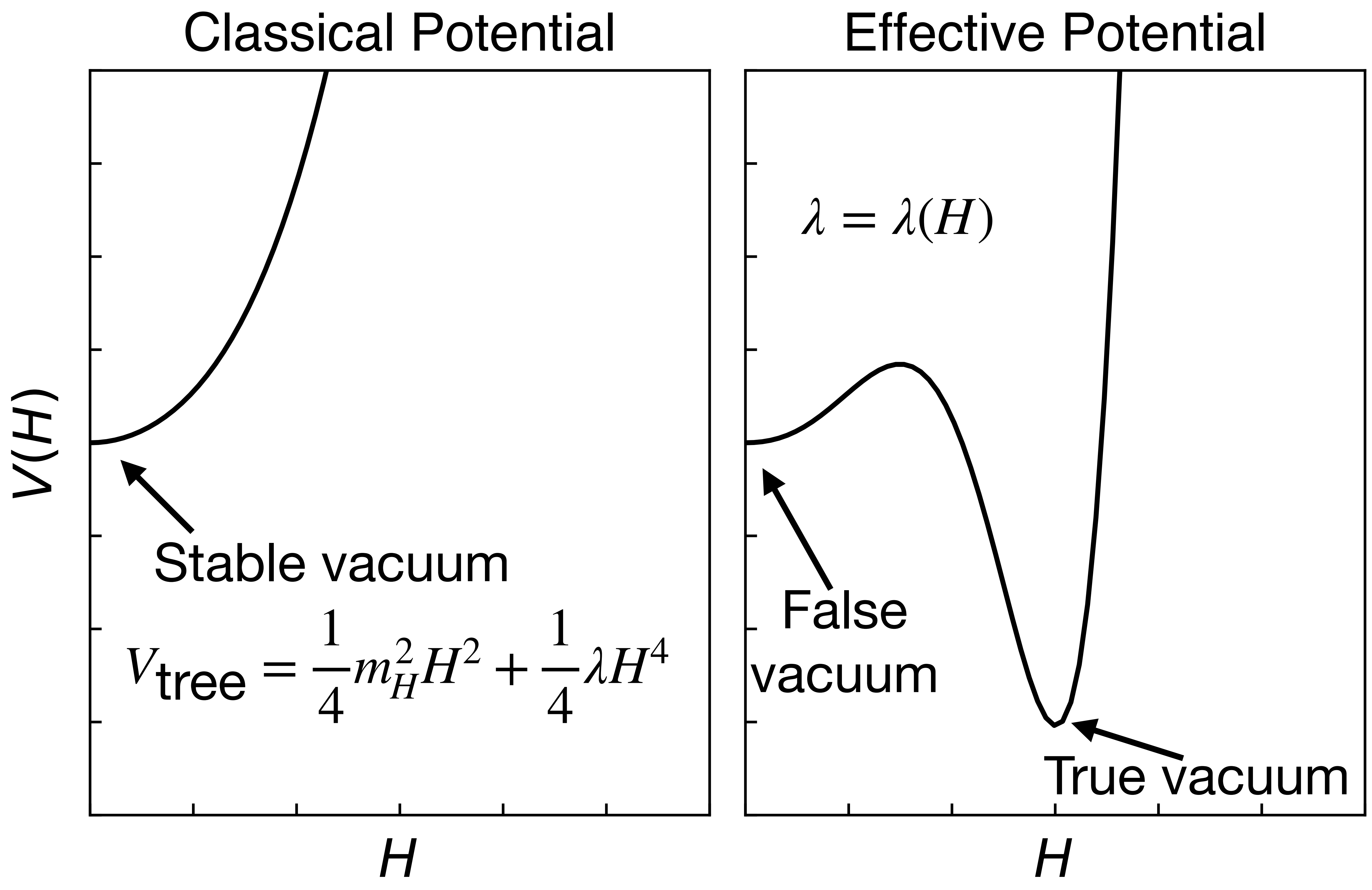
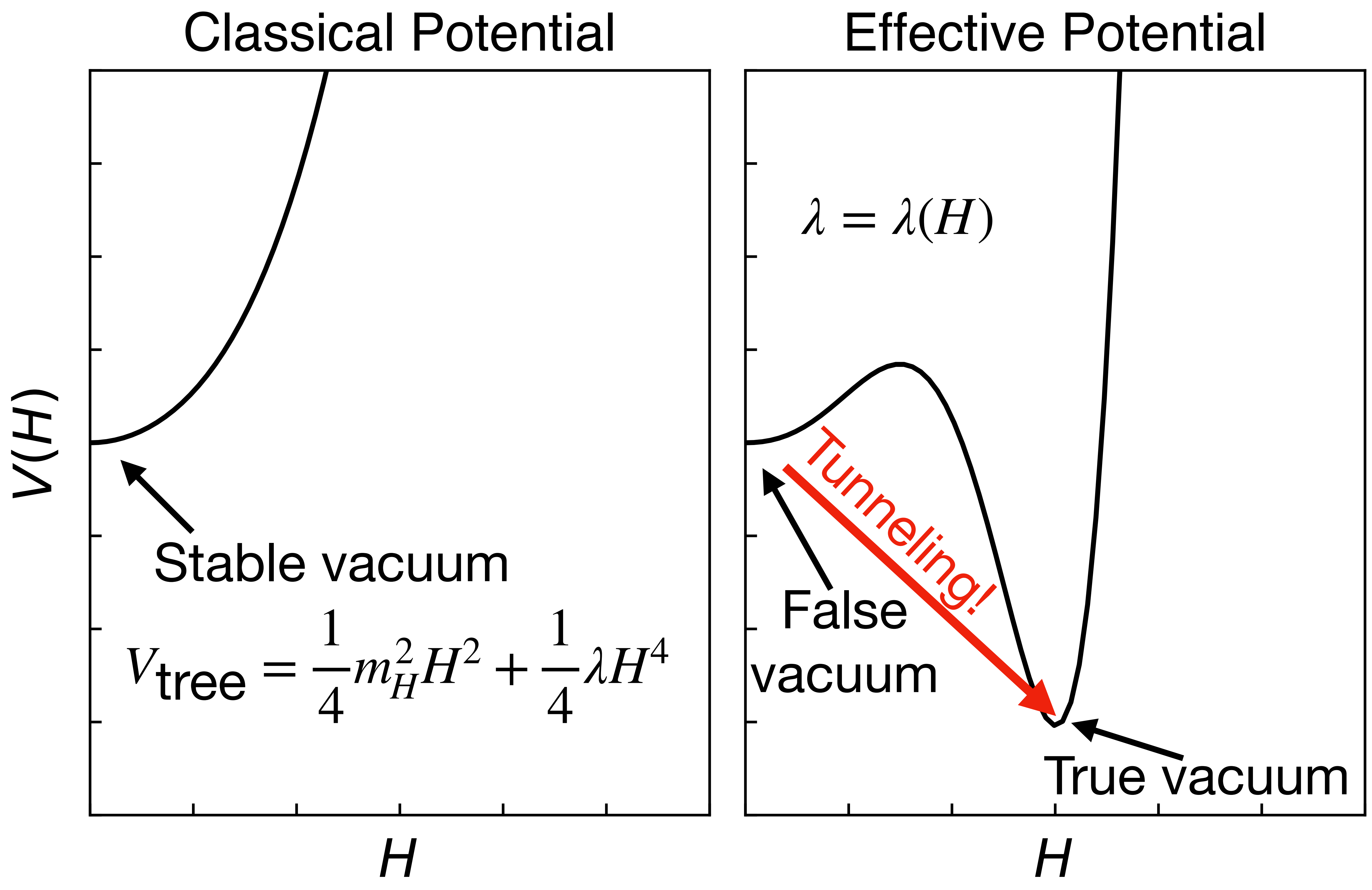
- Quantum mechanics: λ runs, $\beta_\lambda \neq 0$, possible to have multiple minima



Electroweak vacuum metastability

- Classically: with $m_H^2 > 0$, the Higgs potential attains a minimum at $H = 0$
- Quantum mechanics: λ runs, $\beta_\lambda \neq 0$, possible to have multiple minima
- When this happens, the classical minimum can be unstable to tunneling!



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b) EFT assumptions

1. New physics comes in the UV at some scale Λ (with Wilson coefficient c_6)
2. The effects of UV physics on metastability can be parameterized by a dimension-6 operator (e.g. metastability doesn't arise due to an interplay of dimension-6 and dimension-8 terms)
   - This (plus metastability) implies both that $c_6 > 0$ and that λ crosses zero at some scale μ_I (about 10^{11} GeV in the Standard Model)

$$V(H) = \frac{1}{4}m_H^2 H^2 + \frac{1}{4}\lambda H^4 + \frac{c_6}{\Lambda^2}H^6$$

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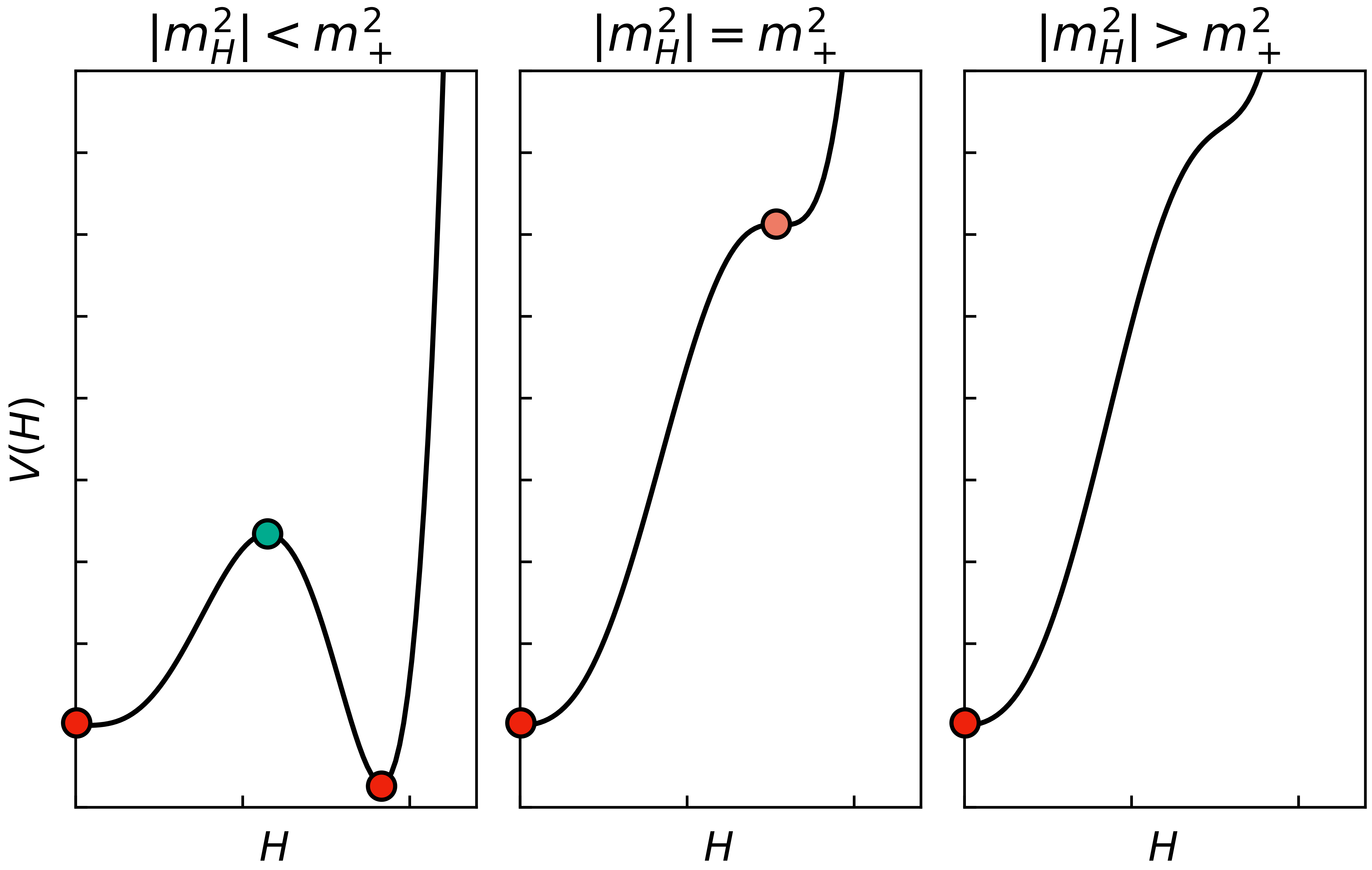
Metastability bounds from above



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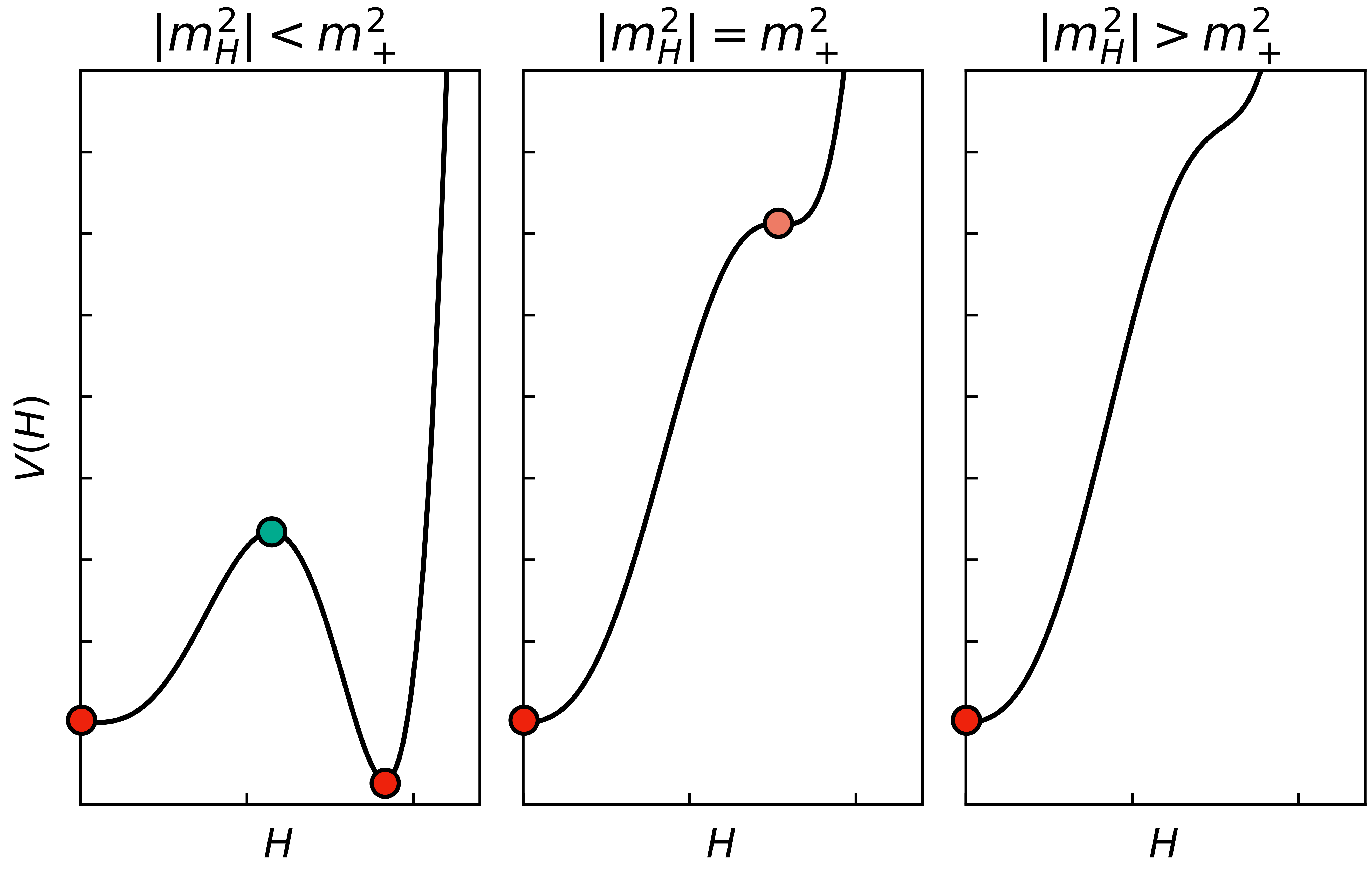
Metastability bounds from above



$$m_H^2 < \frac{\beta^2 \Lambda^2}{48 c_6} W_{-1}(\xi)\left(2 + W_{-1}(\xi)\right) \equiv m_+^2$$

$\mu_I \equiv$ scale where $\lambda = 0$

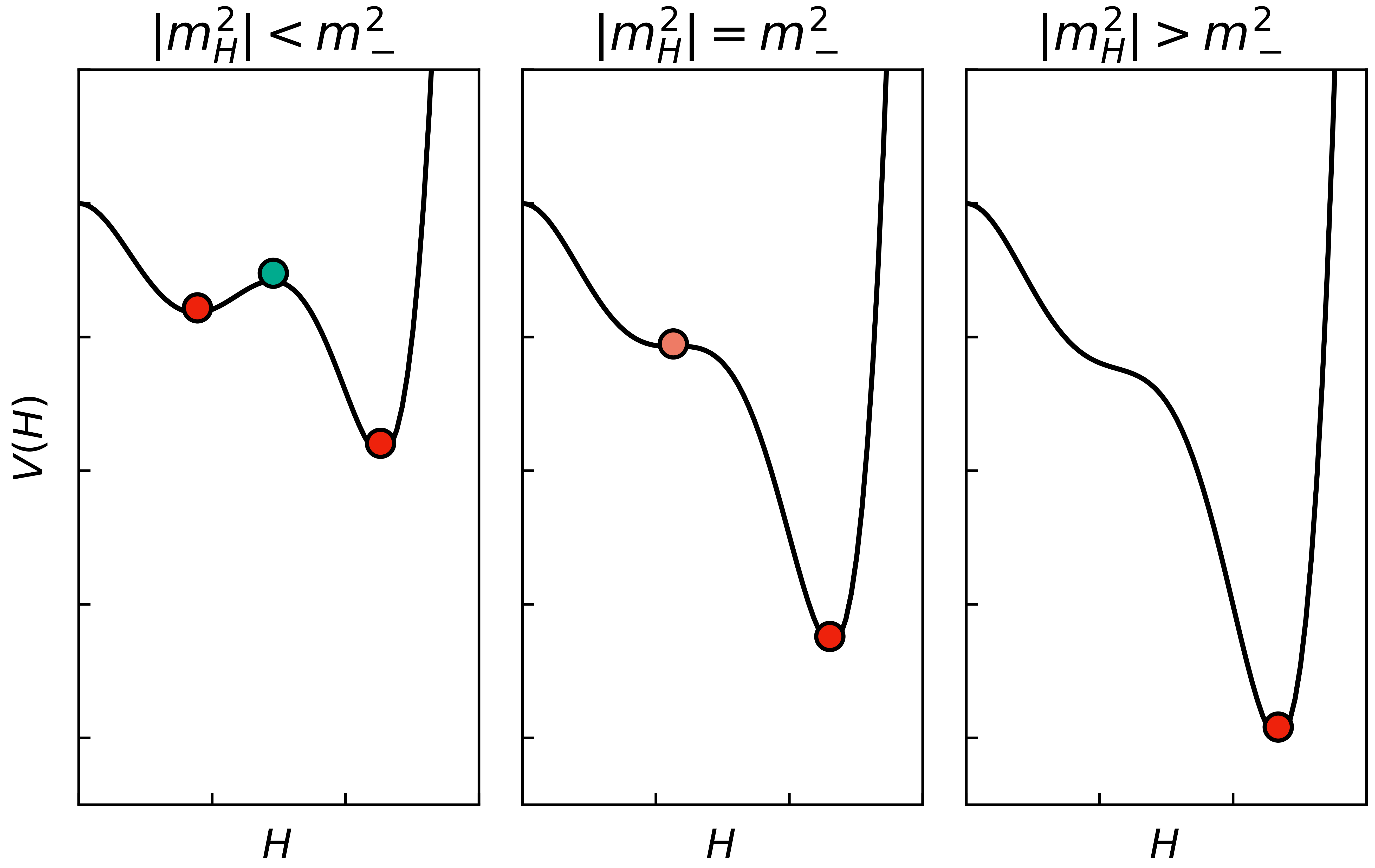
$$\beta \equiv |\beta_\lambda(\mu_I)|$$

$$\xi \equiv \frac{-24 c_6 \mu_I^2}{\Lambda^2 \beta e^{3/2}}$$

Metastability bounds from below

If $m_H^2 < 0$: $$|m_H^2| < \mu_I^2 \beta \exp(-3/2) \equiv m_-^2$$

(derived by Buttazzo et al. 1307.3536, receives corrections c.f. Khoury, Steingasser 2108.09315)



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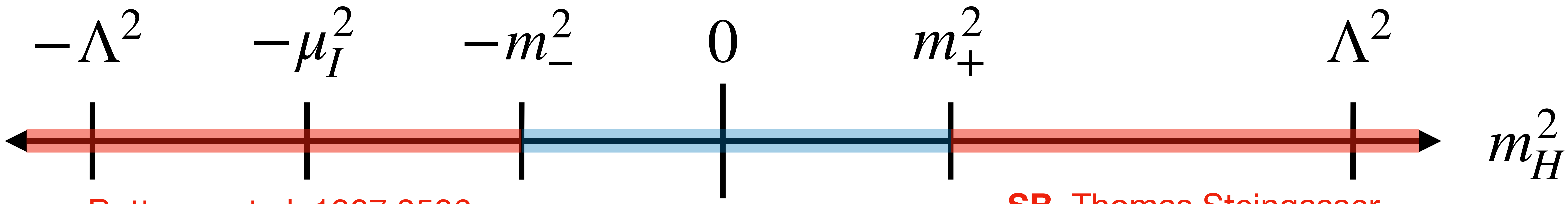

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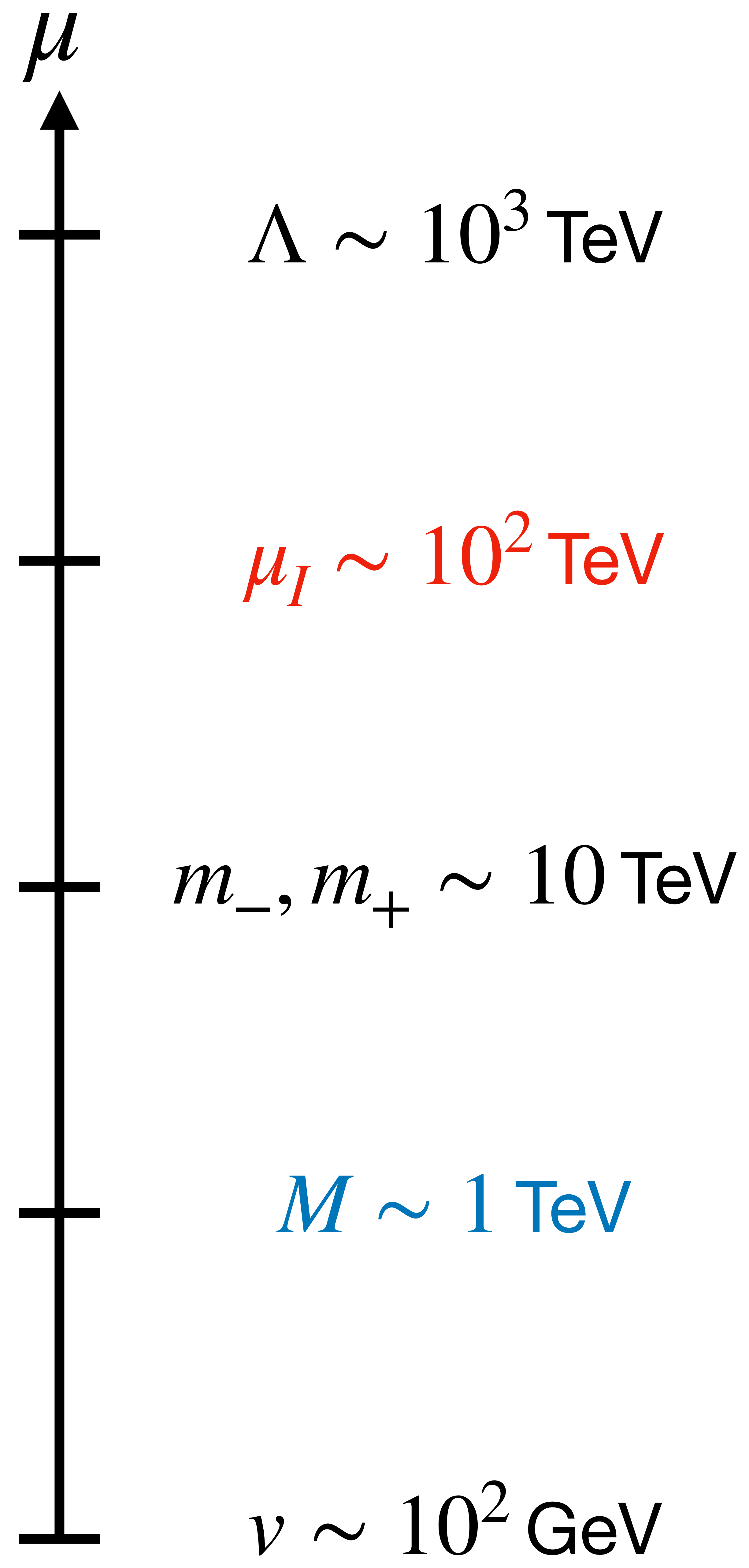
$$-m_-^2 \equiv \boxed{-\mu_I^2 \beta \exp(-3/2) < m_H^2 < \frac{\beta^2 \Lambda^2}{48 c_6} W_{-1}\left(\xi\right)\left(2 + W_{-1}\left(\xi\right)\right)} \equiv m_+^2$$

Model building challenge: to bring these bounds closer to the electroweak scale, can we lower Λ and μ_I simultaneously without ruining metastability? (yes)

Example: Right-handed neutrinos

- Intuition: lower μ_I from its SM value with new Yukawa couplings
- For simplicity, we will use TeV scale right-handed neutrinos (ask me about details if you're curious, same model as Khoury, Steingasser 2108.09315)
- Model characterized by two parameters, neutrino mass scale M and Yukawa coupling y_ν



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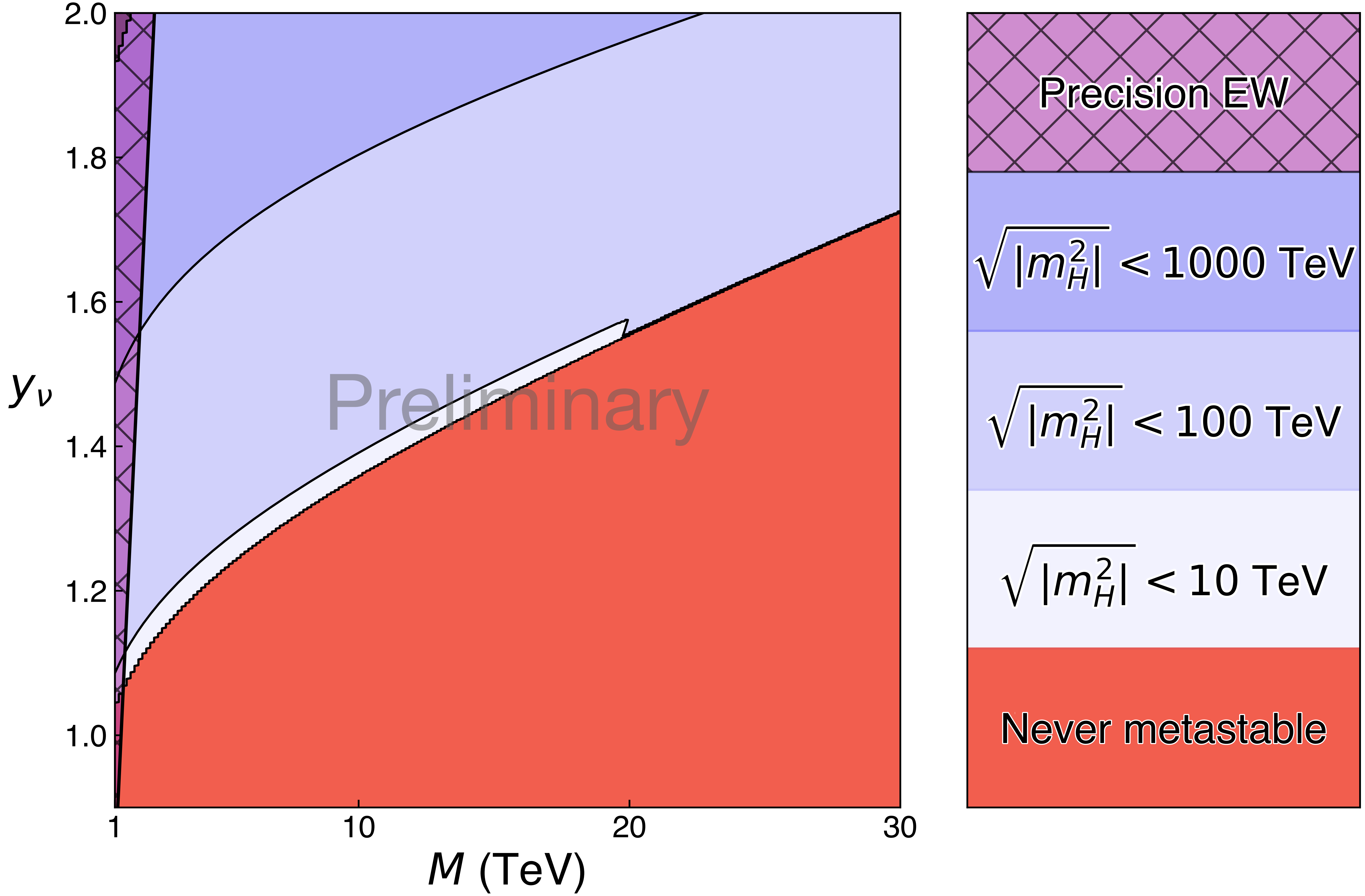
$\Lambda = 1000$ TeV projections



Precision EW quoted from Chauhan, Steingasser 2304.08542

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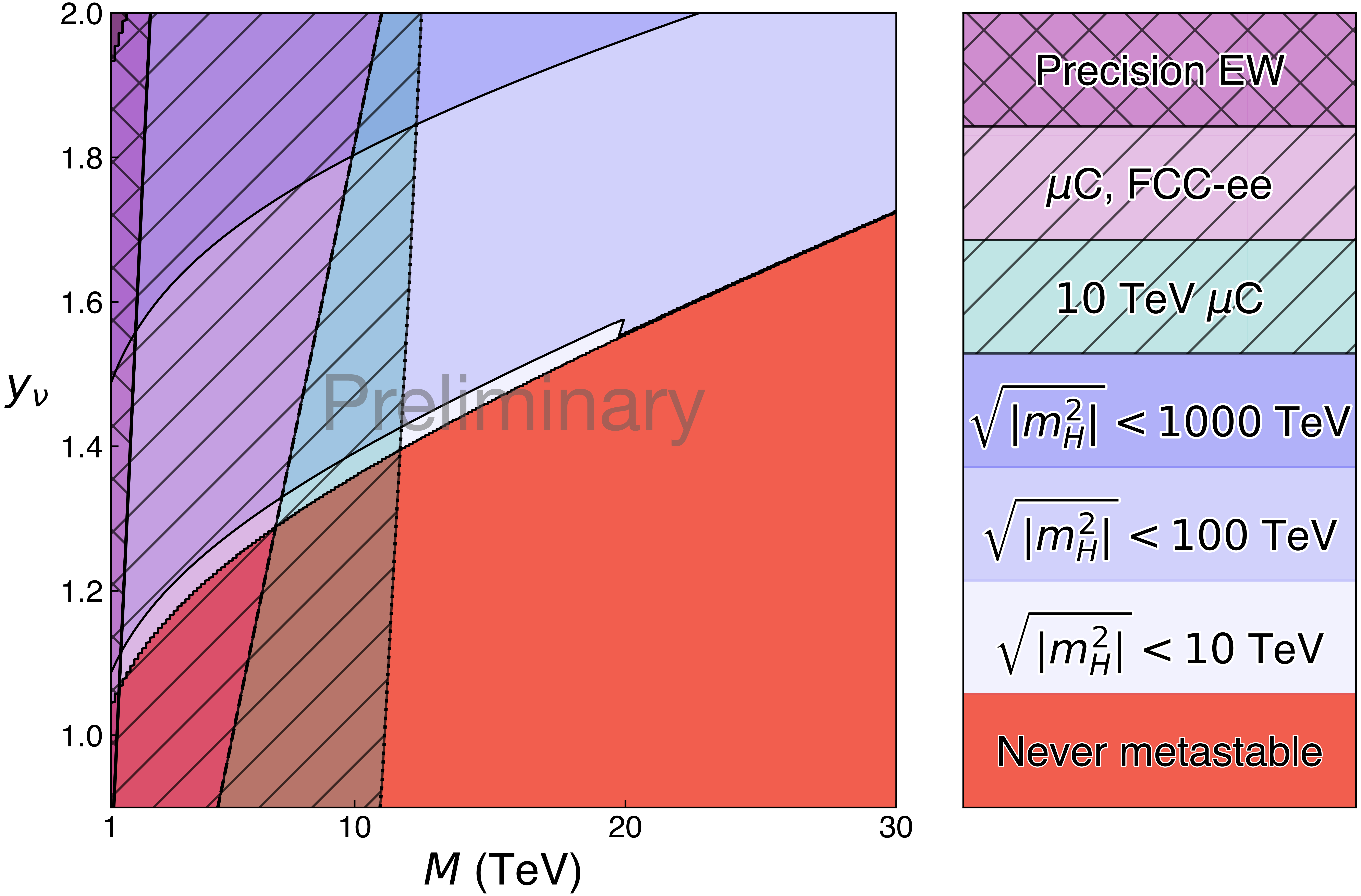
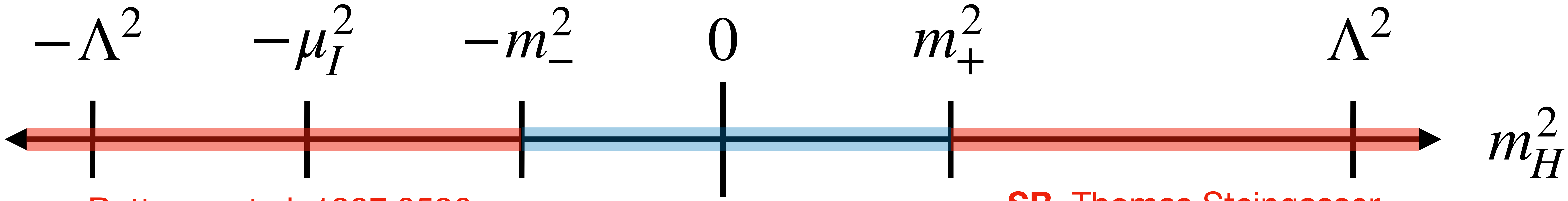


μC bound from Mekala, Reuter, Zarnecki 2301.02602

FCC-ee bound from Antusch, Cazzato, Fischer 1612.02728

Conclusion

- Requiring metastability, imposing conditions on the SM EFT, and fixing SM couplings to their observed values in the IR places bounds on m_H^2 from above and below
- Bringing these bounds toward the electroweak scale requires new physics at $O(1-10\,\text{TeV})$; this scenario can be probed at future colliders
- Things I left out (**SB**, Thomas Steingasser, Sokratis Trifinopoulos 2406.xxxxx)
  - What requirements on the parameters does the lifetime impose?
  - What about models besides RHNs?



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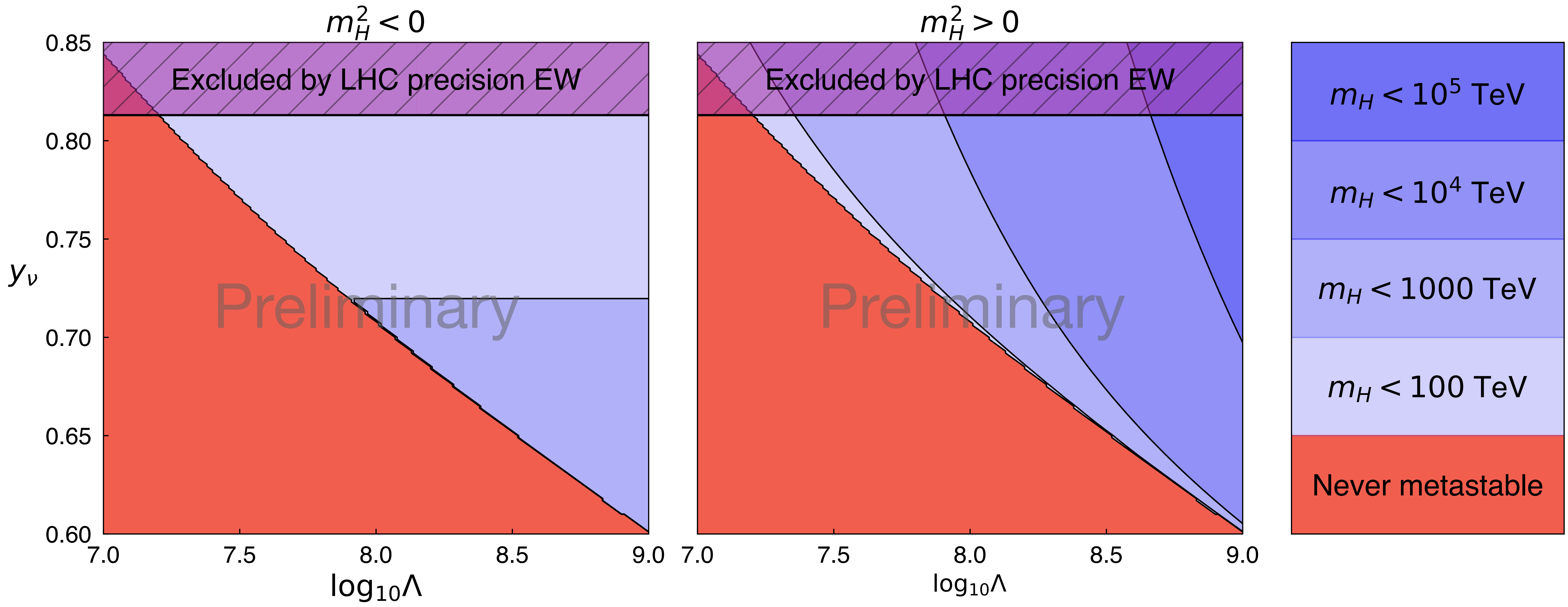
M = 1 TeV split up



EW precision bound quoted from Chauhan, Steingasser 2304.08542

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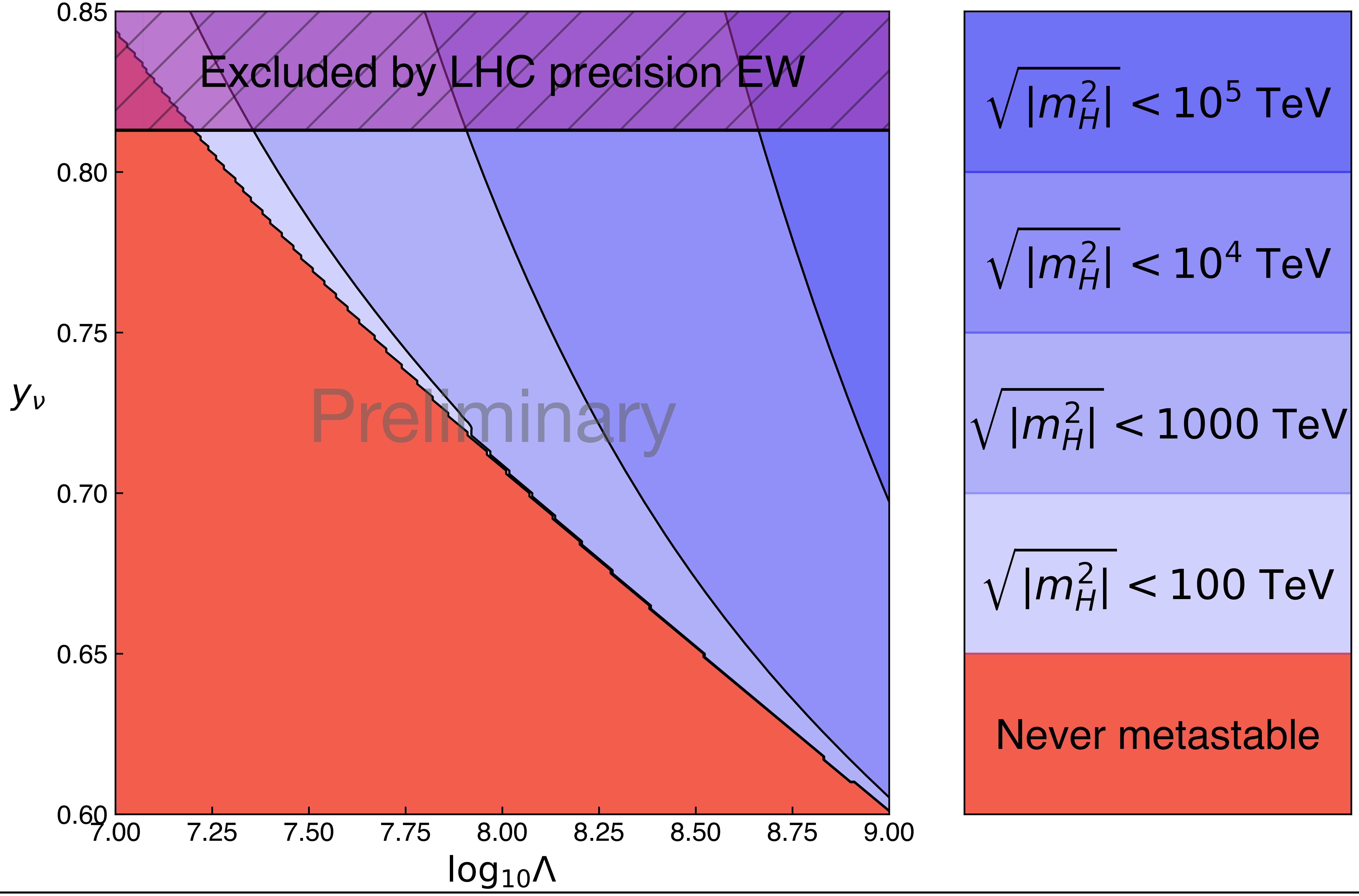
M = 1 TeV combined



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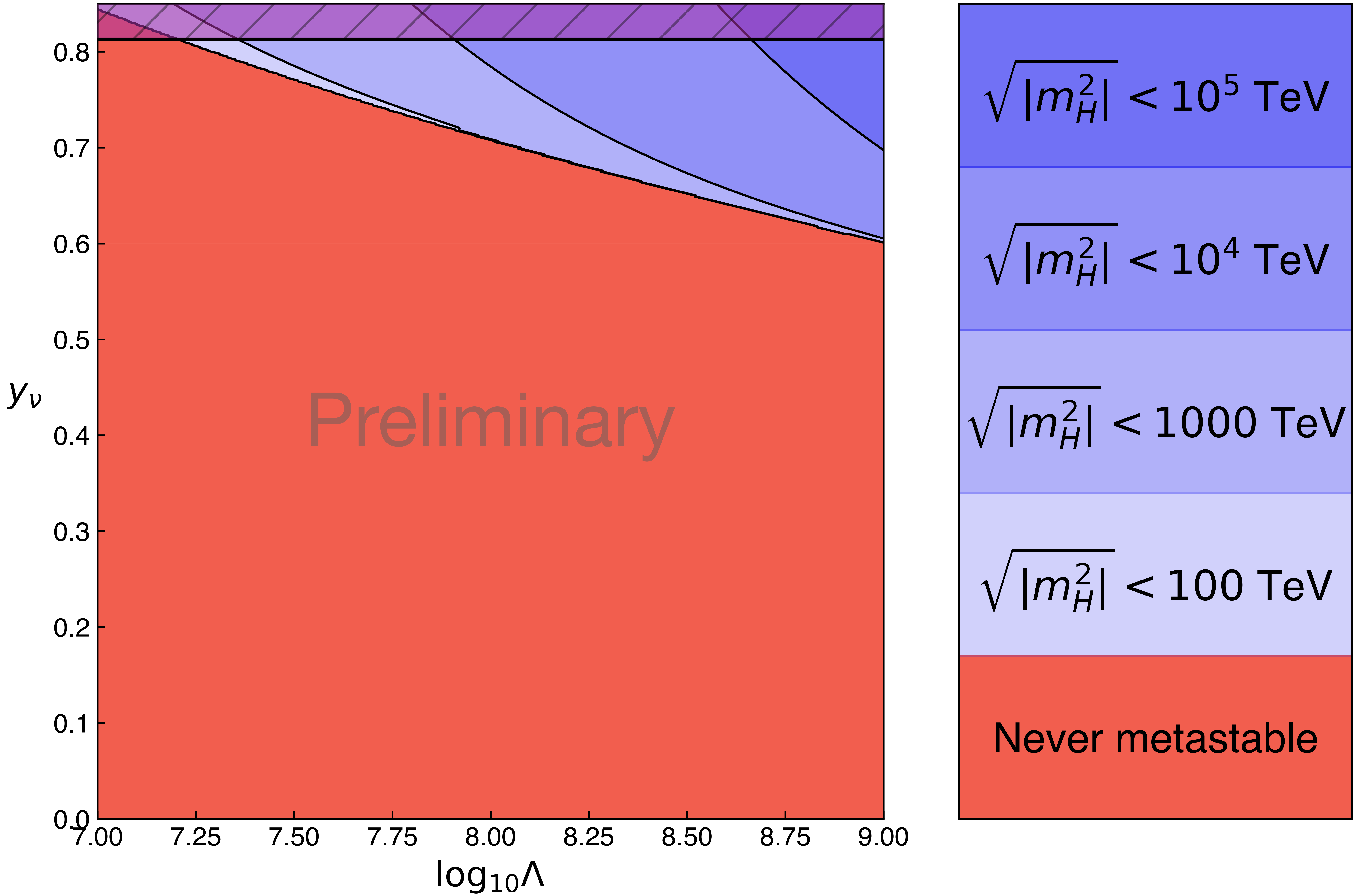
M = 1 TeV projections



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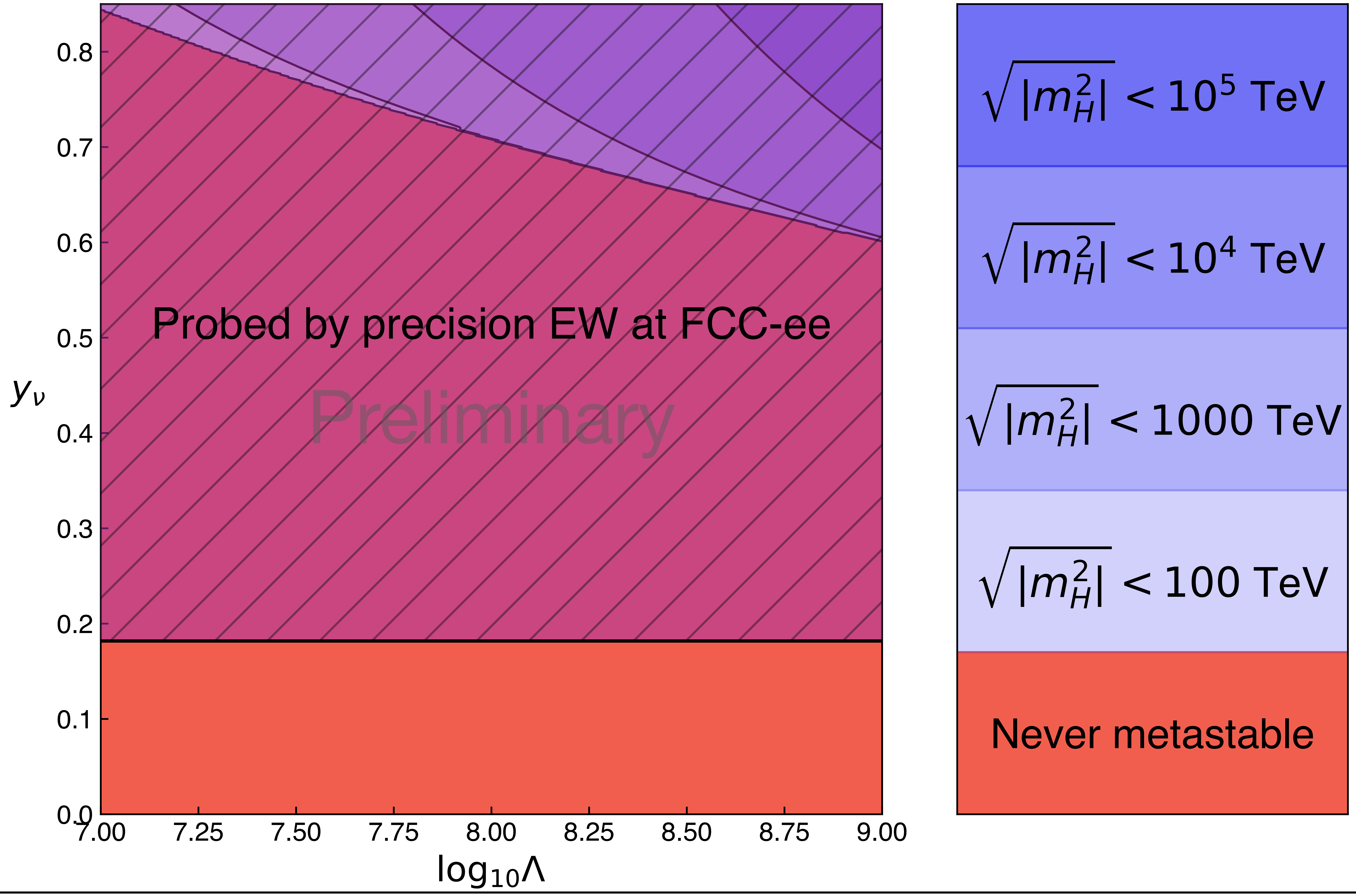

FCC-ee bound from Antusch, Cazzato, Fischer 1612.02728

Low scale seesaw

- Naively, for observed neutrino masses, seesaw mechanism requires RHN mass scale $M \gg$ TeV
- However, this dimensional analysis can fail due to nontrivial matrix structure; can have RHNs that explain observed neutrino masses at low scales if we impose a modified lepton number symmetry (requires 3 RHNs)
- In this case, for the purposes of the electroweak vacuum, there are only two free parameters of the RHN model, the degenerate mass scale M and a parameter characterizing the Yukawa structure, which we take to be y_ν